



TECHNICAL NOTE

D-546

EXPERIENCE WITH A THREE-AXIS SIDE-LOCATED CONTROLLER
DURING A STATIC AND CENTRIFUGE SIMULATION OF THE
PILOTED LAUNCH OF A MANNED MULTISTAGE VEHICLE

By William H. Andrews and Euclid C. Holleman

Flight Research Center
Edwards, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON

November 1960

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL NOTE D-546

EXPERIENCE WITH A THREE-AXIS SIDE-LOCATED CONTROLLER
DURING A STATIC AND CENTRIFUGE SIMULATION OF THE
PILOTED LAUNCH OF A MANNED MULTISTAGE VEHICLE

By William H. Andrews and Euclid C. Holleman

SUMMARY

An investigation was conducted to determine a human pilot's ability to control a multistage vehicle through the launch trajectory. The simulation was performed statically and dynamically by utilizing a human centrifuge. An interesting byproduct of the program was the three-axis side-located controller incorporated for pilot control inputs. This method of control proved to be acceptable for the successful completion of the tracking task during the simulation.

There was no apparent effect of acceleration on the mechanical operation of the controller, but the pilot's control feel deteriorated as his dexterity decreased at high levels of acceleration.

The application of control in a specific control mode was not difficult. However, coordination of more than one mode was difficult, and, in many instances, resulted in inadvertent control inputs. The acceptable control harmony at an acceleration level of 1 g became unacceptable at higher acceleration levels. Proper control-force harmony for a particular control task appears to be more critical for a three-axis controller than for conventional controllers. During simulations in which the pilot wore a pressure suit, the nature of the suit gloves further aggravated this condition.

INTRODUCTION

The large increase in performance of future manned flight vehicles may produce acceleration environments which could render present flight controllers inadequate. Consequently, in recent control concepts the use of side-located or finger-tip-type controllers is being considered for manual guidance of these advanced vehicles.

The incorporation of a side-located controller is by no means a new innovation. Reference 1 presents the results of a study to determine basic design criteria for two-axis side-located controllers. Also, simulator studies incorporating a pitch-roll chair to reproduce longitudinal motions of an airplane have been conducted in which pilot control was provided through a power control system and a two-axis side-located control stick. Controllers of this type have proved satisfactory during flight tests in conventional jet aircraft (refs. 2 and 3). Many analog-simulation studies (for example, ref. 4) were conducted to determine the effectiveness of jet reaction controls in controlling vehicle attitude in the region of low dynamic pressure. A three-axis controller was used in these studies. However, within the scope of these papers, research utilizing a three-axis controller in high-acceleration fields and conditions of rapidly changing dynamic pressure is practically nonexistent.

In recent studies, piloting problems associated with control of the launch of multistage vehicles and the effect of the actual launch-acceleration environment on the control task were investigated during static and dynamic simulator programs. The three-axis-controller concept was selected for the pilot's control during these tests in order to minimize the acceleration effects on controller manipulation. The static simulator program was performed at the NASA Flight Research Center, Edwards, Calif., and the dynamic simulator program was conducted on the human centrifuge of the Naval Air Development Center, Johnsville, Pa. A general description of the program and an analysis of these investigations are presented in reference 5. This paper presents only the details of the controller used in the investigations and the results of the simulator programs pertinent to the controller.

SYMBOLS

a_x	longitudinal acceleration, g units
a_z	normal acceleration, g units
F_θ	pitch-control force, lb
F_ψ	yaw-control force, lb
g	acceleration due to gravity, ft/sec ²
K_θ	spring constant in pitch-control mechanism, lb/in.

K_{ϕ}	spring constant in roll-control mechanism, lb/in.
K_{ψ}	spring constant in yaw-control mechanism, lb/in.
q	dynamic pressure, lb/sq ft
T_D	time delay in engine firing at staging, sec
T_{ϕ}	roll-control torque, in-lb
t	time, sec
α	angle of attack, deg
β	angle of sideslip, deg
γ_a	actual flight-path angle, deg
γ_p	programed flight-path angle, deg
$\Delta\gamma$	'flight-path-angle error $(\gamma_p - \gamma_a)$, deg
δ	controller angular displacement, deg
δ_{θ}	controller angular displacement in pitch, deg
δ_{ϕ}	controller angular displacement in roll, deg
δ_{ψ}	controller angular displacement in yaw, deg
E	integrated tracking error with time, deg-sec
θ	vehicle pitch angle, deg
ϕ	angle of roll, radians
ψ	angle of yaw, radians

Subscript:

max maximum

CONTROLLER AND TESTS

Controller

The three-axis side-located controller (figs. 1 and 2) used in this investigation was designed to minimize the effects of acceleration on the piloting control task. It was assumed that the pilot's forearm would be restrained and that the control of pitching, rolling, and yawing motions would be executed through the rotational limits of hand movement, essentially pivoted at the wrist. The three axes of motion are not necessarily coincidental, inasmuch as the control grip can be adjusted longitudinally to fit the individual pilot's arm length. The controller limits of angular displacement in the pitch and roll modes are $\pm 30^\circ$, and the yaw mode is limited to $\pm 20^\circ$. These limits were selected on the basis of average hand-movement capability. A longitudinal-trim switch (thumb type) was mounted on the top of the control grip.

The controller was designed to incorporate the following characteristics:

Light weight and low inertia

Adjustable force and breakout characteristics

Force proportional to deflection

Electrical-type control

Static and dynamic balance

Adjustable geometry

To provide acceptable, yet versatile, force characteristics, the cam mechanisms illustrated in figure 3 were designed for the respective control modes. The shape of the cam and the characteristics of the preload spring in the cam follower determine the force gradients, breakout forces, and positive centering of the stick. This design permits easy alteration of force characteristics. The force characteristics selected, on the basis of pilot opinion, during the static and the centrifuge programs are presented in figure 4.

To convert the controller displacement to proportional electrical signals, conductive, plastic-type Markite potentiometers, rated at 50,000 ohms, were geared to the handle pivots of the controller. These potentiometers were used inasmuch as they operate at a low noise level, provide good linearity and resolution characteristics, and require a low-level torque for satisfactory performance.

The controller was statically balanced with the spring and follower removed from the cam mechanism. Several unmanned dynamic runs were made during the centrifuge program to determine the assembled balance characteristics under accelerated conditions. The effects of acceleration on controller balance were not detectable.

Tests

Launch.- The three-axis controller was evaluated during a simulator investigation designed to determine the human pilot's ability to control two- and four-stage vehicles to the desired injection conditions of velocity and altitude. Fixed-base and dynamic simulations of the problem were performed. For both simulations, the vehicle aerodynamics were generated by an analog computer. Since the launch-control task was programed to be primarily a task in the pitch plane, the computer mechanization incorporated three degrees of freedom in the longitudinal mode; the lateral and directional modes were simplified to include only terms necessary to introduce roll and yaw disturbances as well as the lateral-directional control terms (see fig. 1 of ref. 5). Figure 5 illustrates the general setup, including the basic control-tracking task presented to the pilot on the instrument panel. For the static simulations, only the visual loop was used, but for the dynamic simulation the human centrifuge actually imposed the problem-commanded accelerations on the pilot.

During the simulated launch, the vehicle flight path approximated a zero-lift gravity turn. To add realism to the control task, a roll-heading error of 30° and disturbances from wind shears, unsymmetrical engine burnout moments, and delays between cutoff and firing of successive stages were included in the simulation. The latter conditions were programed at random, and the pilot was required to make the necessary corrections in conjunction with the basic longitudinal tracking task. Various levels of vehicle longitudinal stability and damping, including conditions of instability and low damping at shutdown of the first stage, were investigated. A detailed description of the test program is presented in reference 5.

For control of the vehicle to a specific launch profile, the pilot commanded engine-nozzle angle through the three-axis controller. The parameters of vehicle attitude, angle of attack α , angle of sideslip β , angle of pitch θ , angle of roll ϕ , and flight-path-angle error $\Delta\gamma$, were presented to the pilot as indicated in figure 5. With the exception of pitch angle, the pilot attempted to maintain these quantities at zero for the desired launch trajectory. Early in the launch, small departures from the desired program resulted in large errors in the final conditions attained. Consequently, continuous tracking was required by the pilot.

During the program, pilots normally wore lightweight flight suits. However, for the dynamic four-stage simulation, the Air Force MC-3, the MC-2, and the Navy Mark IV pressure suits were worn by several of the pilots to determine the effect of the suit on pilot performance. Only the Air Force MC-3 suit was pressurized during the runs.

Control harmony.- Throughout the dynamic program, constructive criticism of the controller operation offered by the pilots indicated that the controller characteristics were not optimum under accelerated conditions. Based on these comments, a brief investigation was initiated, primarily to determine optimum force characteristics. This study was designed to investigate coordinated maneuvers with the controller by controlling the horizontal (roll control) and vertical (pitch control) movement of a dot on an oscilloscope with the roll and pitch control. The pilot, under static conditions, was required to track the lines 1 to 12 shown in figure 6 at a slow, a medium, and a fast rate. The tracking paths similar to number 1 represent coordinated control inputs, while the tracking paths similar to 2 represent an initial roll motion followed by a pitch motion at a predetermined roll angle. A measure of the harmony of the controller was obtained by recording the integrated tracking error and the inadvertent control input in the control mode not being commanded. Combinations of control-force and breakout characteristics were investigated to improve the control harmony.

H
1
5
2

RESULTS AND DISCUSSION

Launch-Control Problem

Staging.- The precise control of the launch trajectory of a manned multistage vehicle during the transition through the earth's atmosphere may pose a critical control problem, inasmuch as the aerodynamic characteristics of the vehicle tend to be inherently unstable. As a result, the vehicle aerodynamics determine the degree of complexity of the control task. In addition, the task is further aggravated when booster staging occurs in this region. Consequently, the control problems in this phase of the launch trajectory were extensively investigated. The three-axis controller was incorporated in an attempt to provide the pilot with acceptable control for successful completion of the task.

Figure 7 presents time histories of a series of dynamic launches during which the effects of longitudinal acceleration on the performance of the task were determined by repeating the same tracking task at levels of acceleration from 3g to 15g. At staging, the programmed vehicle-stability characteristics were stable with good damping. Random disturbances were introduced as indicated in the time histories.

The deviations of the flight-path-angle error $\Delta\gamma$ and the angle of attack about zero are measures of the pilots' performance. During the initial 20 seconds from launch, the programed flight-path angle γ_p changed from 85° to 57° . Consequently, it was more difficult to follow the program in this region. In figures 7(a) and 7(b) the large initial program error was practically nullified within approximately 30 seconds, and the desired flight path was attained. As the rate of acceleration onset was increased in the succeeding runs (figs. 7(c) to 7(e)), it was more difficult to eliminate the program error; however, the pilot still maintained the flight-path angle γ_a within 1.5° of the programed angle.

When disturbances of wind shear and the initial heading error in roll were introduced in the tracking task (figs. 7(a) to 7(c)), the pilot had no difficulty in recognizing the disturbances and making the proper control correction. However, in the runs illustrated by figures 7(b), 7(d), and 7(e), where no yaw disturbances are introduced, the yaw angle drifts approximately 0.08 radian to the left. The pilot commented on the drift and believed it was characteristic of the instrument under accelerated conditions. This condition might well have existed; however, it is believed that the small yaw-control pulses noted in the yaw-control time history are generally inadvertent control motions and contribute to the apparent yaw drift.

Complete launches.- Although the severest control task occurred during the initial part of the launch previously discussed, the control tasks associated with complete four- and two-stage launch maneuvers were also investigated. Presented for comparison in figures 8(a) and 8(b), respectively, are static and dynamic four-stage simulated launches. In these maneuvers, the vehicle was unstable, with low damping at the conclusion of the first stage. Random disturbances for wind shears were introduced, as is indicated. In both the static and dynamic runs the control task was demonstrated to be well within the capability of the human pilot. During the dynamic run, the flight-path-angle error $\Delta\gamma$ and the excursions in angle of attack appear to be less than those during the static run. This can be attributed to a higher degree of motivation by the pilot during the dynamic run.

Also investigated was the control task associated with the launch of a typical two-stage vehicle. Presented in figure 9 is a time history of a two-stage launch with the same vehicle characteristics of figure 8. The primary difference between the two- and four-stage configuration is the acceleration profile. The control task is not as severe for the two-stage configuration as for the four stage, since staging occurs at a lower dynamic pressure ($q \approx 500$ psf for two stage, $q \approx 1,500$ psf for four stage) and offsets the effect of staging at a higher longitudinal acceleration. This control task, too, proved to be well within the capability of the human pilot. Accelerations up to the maximum obtained in these launches had no apparent influence on the pilot's ability to

control the task, and the three-axis controller proved to be an effective method of control for the complete launch maneuver.

Pilots' Comments

Static tests.- Comments concerning the operation of the controller were obtained from the pilots during the programs. Following the static program, the pilots concluded that the controller was satisfactory for this control task. The breakout and force gradients were considered to be fair-to-good, with acceptable centering. The pilots were skeptical of their ability to coordinate three axes of control until they realized that the controller was not to be utilized as a conventional airplane controller. The concept then became more acceptable.

H
1
5
2

Dynamic tests.- During the dynamic launch-simulation program, all pilots agreed that obtaining the desired amount of control at high acceleration was more difficult than at low acceleration. The controller did not appear to be affected by the acceleration forces, but the control task became more difficult as dexterity diminished. Control harmony, which was acceptable at 1 g, became unacceptable at high acceleration. The original controller-force gradient and breakout in both yaw and pitch were considered to be low at high g. Most of the pilots felt that the roll breakout force was high at low g and that positive control centering was not apparent in the high g conditions. In an attempt to avoid inadvertent control inputs, the pilots used the roll control as an on-off control. There was some correlation between roll-control inputs and inadvertent yaw inputs, which indicated poorer than anticipated control harmony.

Figure 10 presents an overall summary of the pilots' ratings of the controller operation for the dynamic centrifuge runs. The various acceleration levels indicate peak accelerations attained during a series of tests. As may be observed, the average ratings of the controller utility varied from good at 3g to acceptable at 12g.

Trim.- Although a trim knob was incorporated for pitch trim, most of the pilots felt that the control task did not require trim. Consequently, the trim was used very little. If the investigation had included the reentry phase of the flight envelope, the trim device may have proved to be more useful. It was concluded that the trim knob was poorly located on the top of the controller grip. A left-hand stick was suggested as a more useful location.

Pressure suits.- The pilots reported some loss in control feel because of the nature of the suit gloves. With the MC-3 suit there was little deterioration in the roll-control mode, but the pitch mode was restricted by glove stiffness at maximum control deflection. With

the MC-2 suit there was some loss in control feel in all three modes of control. The Mark IV suit incorporates a wrist ring which seriously affected the roll and yaw control feel and the pilot's ability to manipulate the control. Increasing the overall dimensions of the controller would relieve this interference.

Control-Harmony Tests

At the completion of the dynamic simulation program, an investigation was conducted to improve the control harmony of the controller. The simple control task presented in figure 6 and discussed in the section on "Tests" was used during the evaluation. Figure 11 presents a comparison of the results obtained with the original force characteristics and the modified force characteristics selected by the pilots as being near optimum for this control task. At the slow and medium rates of control input, the increased yaw-force gradient reduces the inadvertent yaw input as would be expected. The reduced roll-force gradient improved the pitch-to-roll control-force harmony and reduced the roll tracking error. During rapid control motions, the modified force combinations noticeably improved the force harmony of the controller, but the tendency to induce inadvertent yaw was still evident during certain coordinated tracking tasks. The problem of coordinating control modes appears to be the major disadvantage of the three-axis side-located controller. In certain tracking areas the physical operation of the wrist and forearm determines the accuracy with which precise control can be applied. For the tracking problem shown in figure 6, tracing the lines in the upper and lower left-hand quadrants generally appears to be the most difficult task. These physical limitations could be avoided by restricting the controller travel, but this solution would result in increased control sensitivity. Table I shows the comparison of the original and modified force characteristics of the controller. Although it was desirable to have a high yaw-force gradient for this control task, different control tasks will probably require different force gradients.

CONCLUDING REMARKS

The three-axis side-located controller proved to be an acceptable method of pilot control of the tracking task presented during the static and dynamic launch simulation of multistage vehicles.

There was no apparent effect of acceleration on the mechanical operation of the controller, but, as dexterity decreased at high levels of acceleration, the pilots' control feel deteriorated.

The application of control in a specific mode, such as pitch, was not difficult. However, coordination of more than one mode (pitch and roll) was difficult and in many instances resulted in inadvertent control inputs. The acceptable control harmony at an acceleration level of 1 g became unacceptable at higher acceleration levels. Proper control-force harmony for a particular control task appears to be more critical for a three-axis controller than for conventional controllers. During simulations for which the pilot wore a pressure suit, the nature of the suit gloves further aggravated this condition.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., August 8, 1960.

REFERENCES

1. Brissenden, Roy F.: Some Ground Measurements of the Forces Applied by Pilots to a Side-Located Aircraft Controller. NACA TN 4171, 1957.
2. Sjoberg, S. A., Russell, Walter R., and Alford, William L.: Flight Investigation of a Small Side-Located Control Stick Used With Electronic Control Systems in a Fighter Airplane. NACA RM L56L28a, 1957.
3. Kuehnel, Helmut A., and Sommer, Robert W.: Flight Investigation of the Acceptability of a Small Side-Located Controller Used With an Irreversible Hydraulic Control System. NACA TN 4297, 1958.
4. Stillwell, Wendell H., and Drake, Hubert M.: Simulator Studies of Jet Reaction Controls for Use at High Altitude. NACA RM H58G18a, 1958.
5. Holleman, Euclid C., Armstrong, Neil A., and Andrews, William H.: Utilization of the Pilot in the Launch and Injection of a Multi-stage Orbital Vehicle. Paper No. 60-16, Inst. Aero. Sci., Jan. 1960.

TABLE I
FORCE CHARACTERISTICS OF THE CONTROLLER

Control	Original			Modified		
	Spring constant, lb/in.	Breakout force, lb	Force or torque at δ_{\max}	Spring constant, lb/in.	Breakout force, lb	Force or torque at δ_{\max}
Pitch	48	± 0.3	2.5 lb	48	± 0.3	2.5 lb
Roll	23	± 0.4	7.4 in-lb	8	± 0.5	5.25 in-lb
Yaw	32	± 0.6	2.3 lb	150	± 1.5	3.5 lb

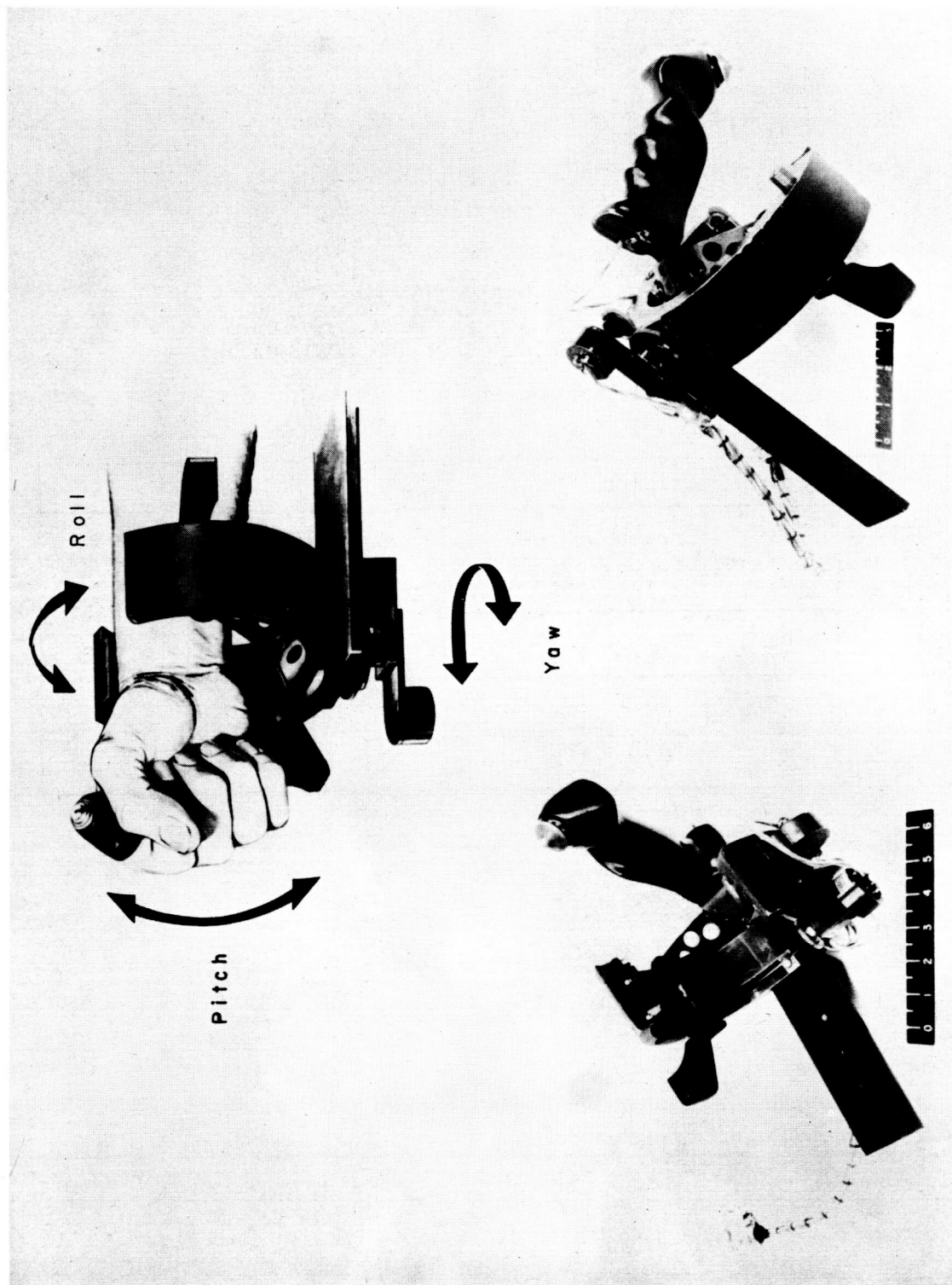
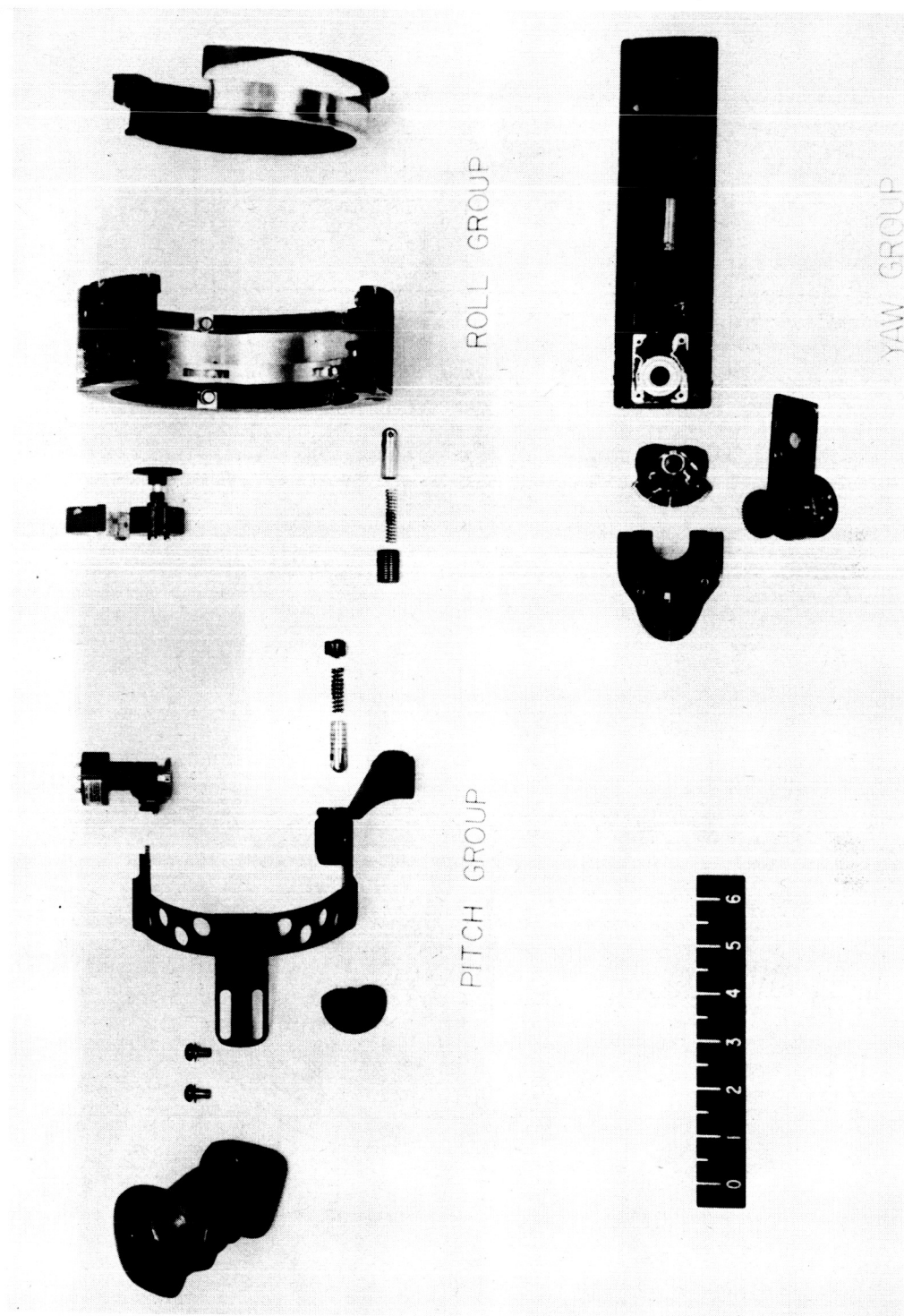
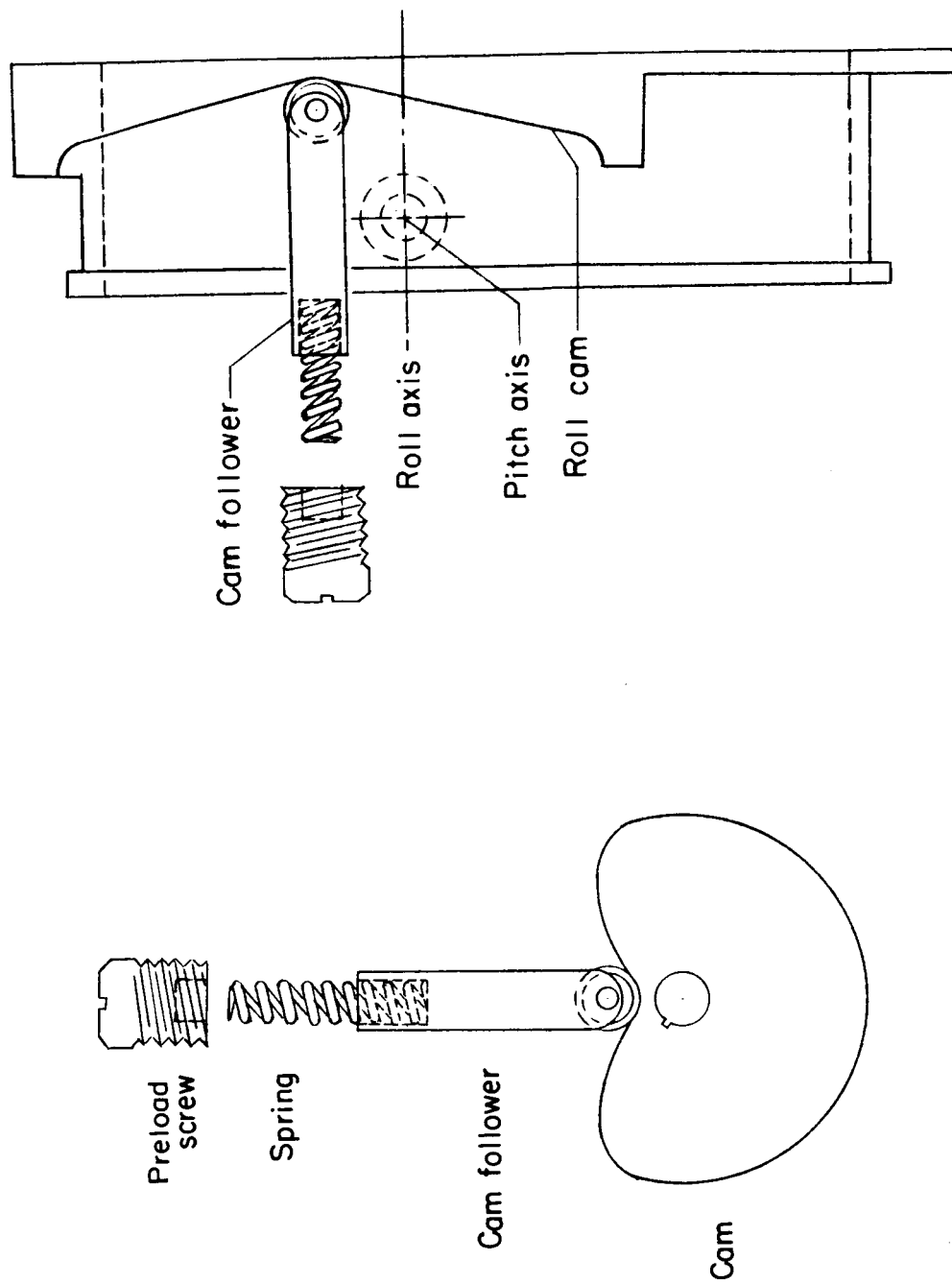


Figure 1.- Views of three-axis side-located controller.



E-4729

Figure 2.- Exploded view depicting assembly of the three-axis controller.



Roll assembly

Pitch and yaw assembly

Figure 3.- Schematic drawing of the cam mechanism incorporated in the three-axis controller to obtain pitch-, roll-, and yaw-force gradients.

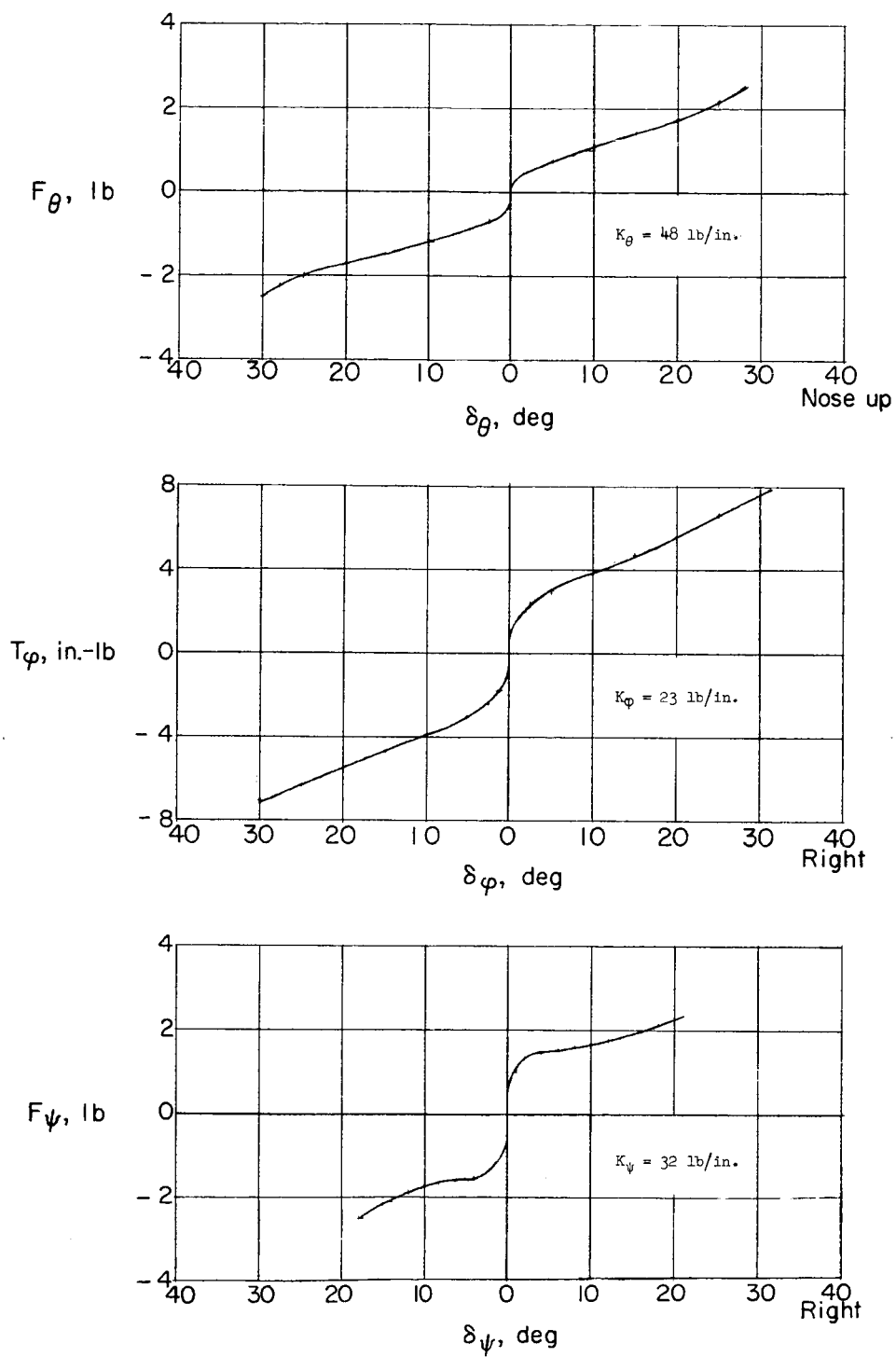


Figure 4.- Force characteristics of the three-axis controller.

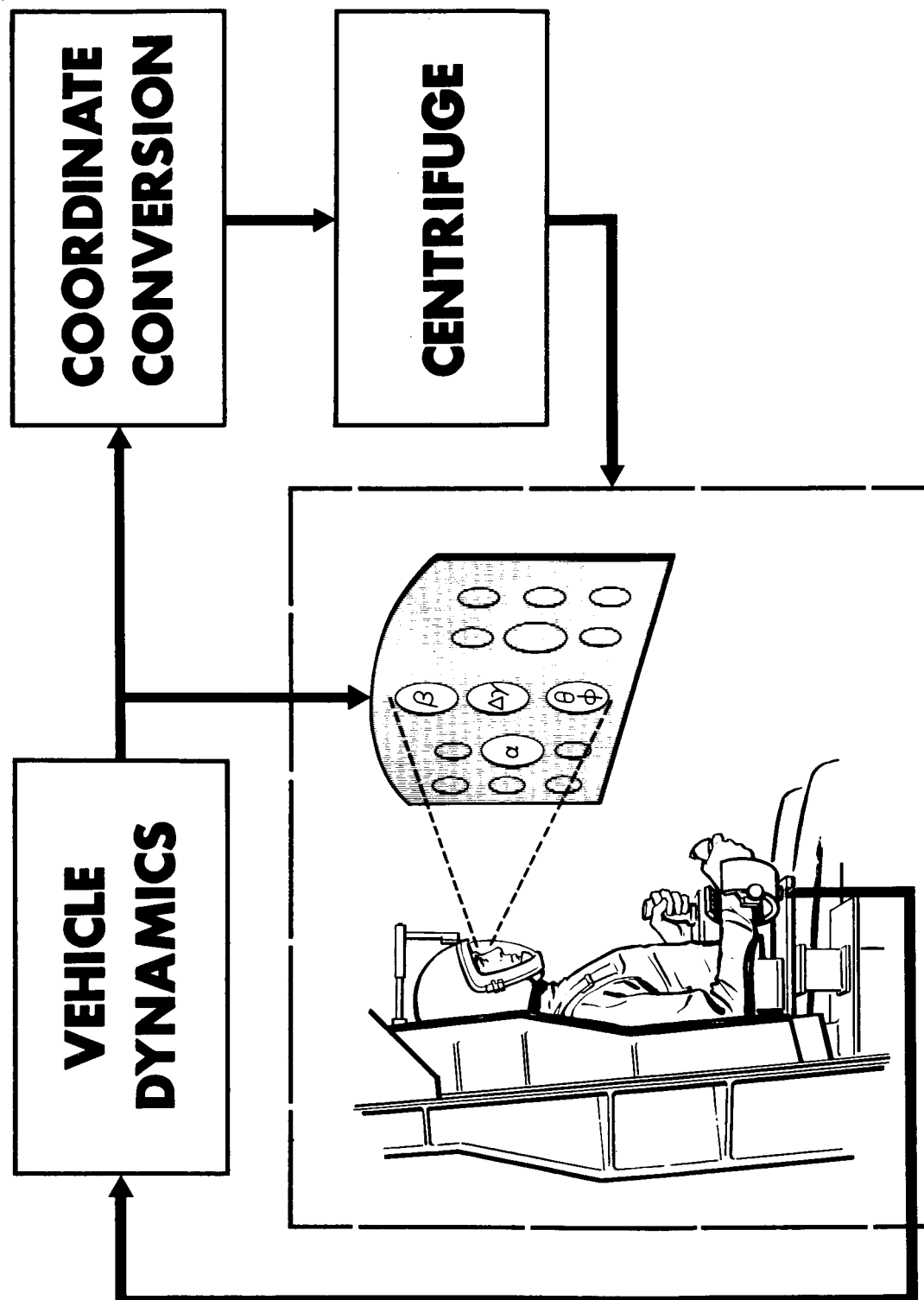


Figure 5.- Block diagram illustrating the simulator setup and primary tracking task.

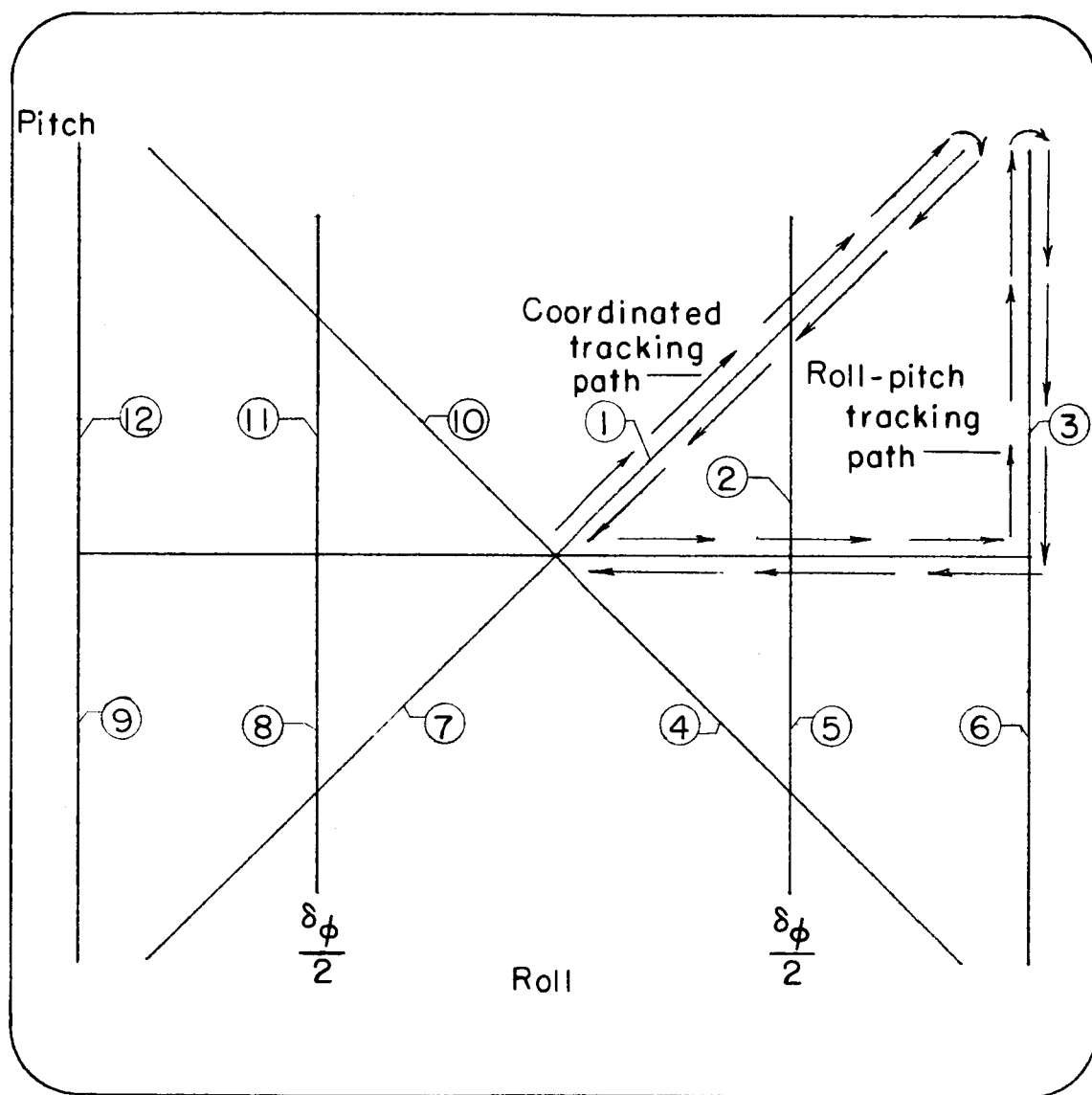


Figure 6.- Tracking task employed in the determination of three-axis force harmony of the side-located controller.

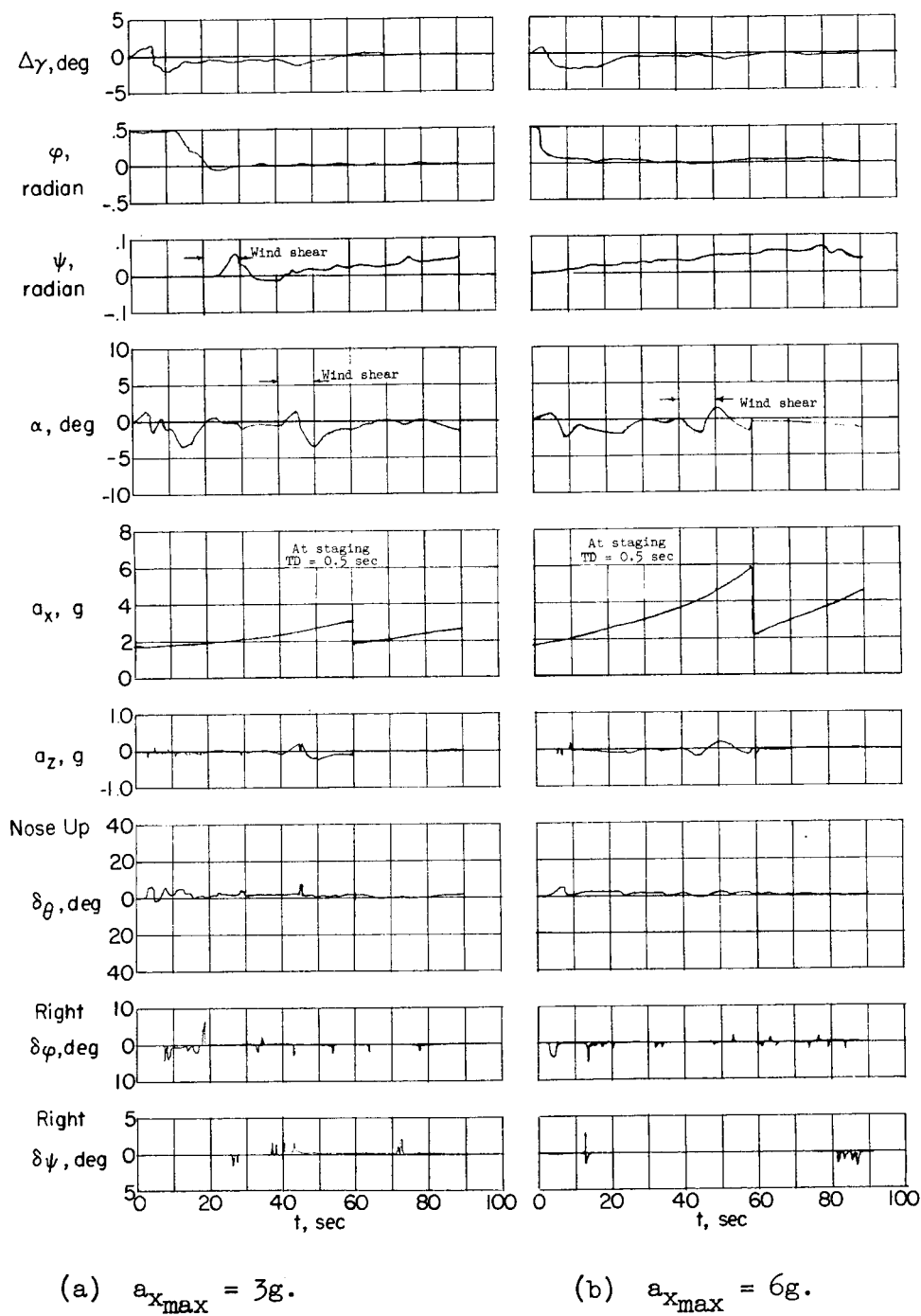
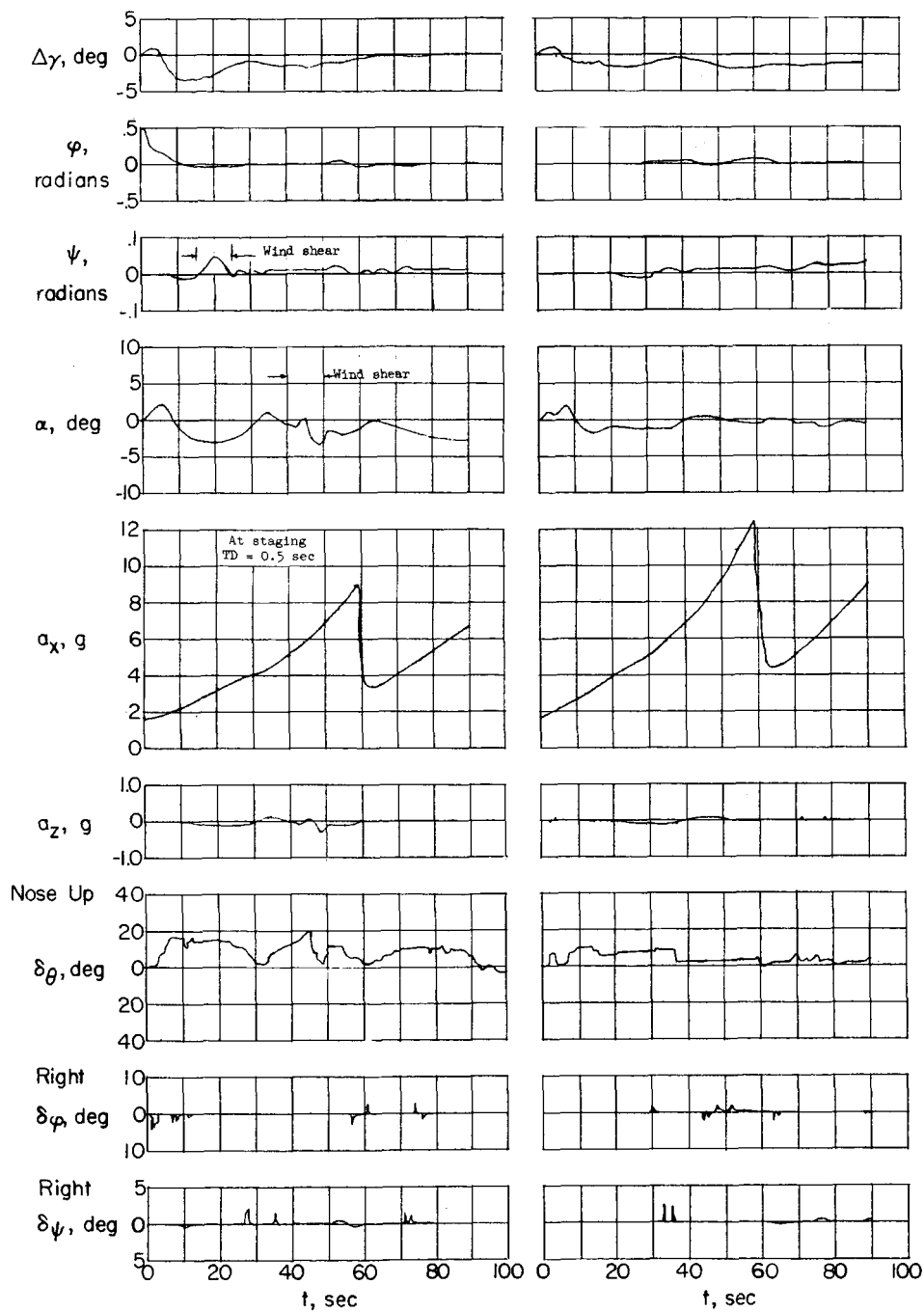


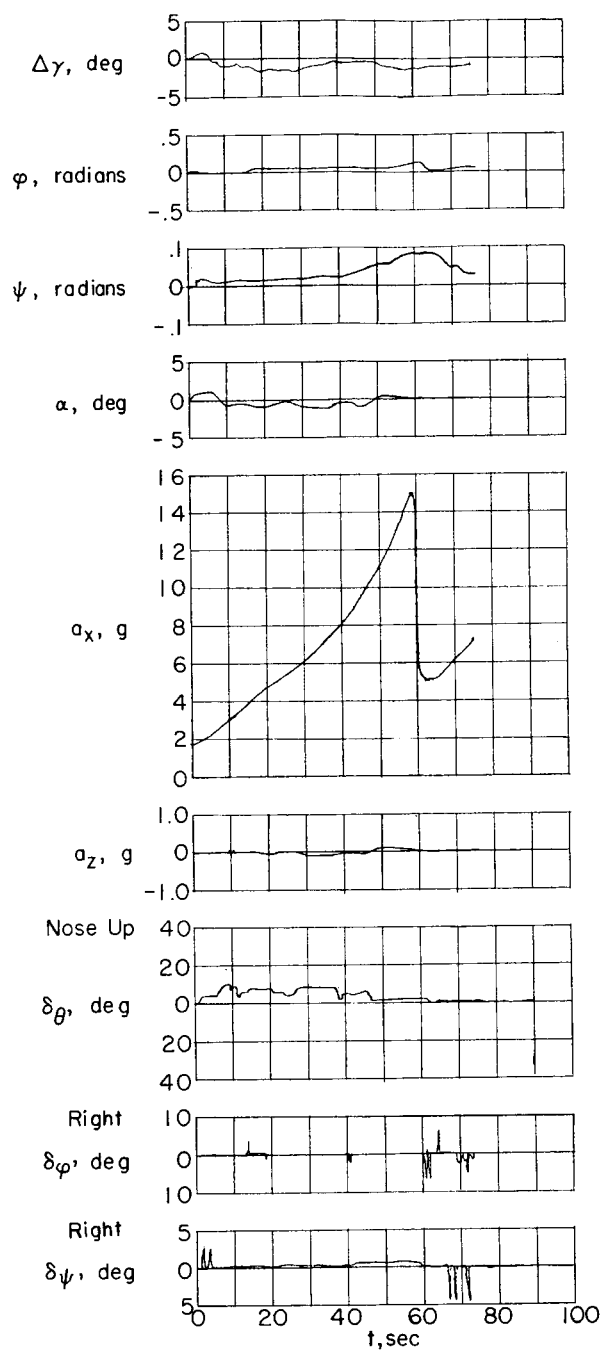
Figure 7.- Time histories of 90-second dynamic runs from $a_{x_{\max}} = 3g$ to $15g$ performed on the centrifuge.



(c) $a_{x_{max}} = 9.0g$.

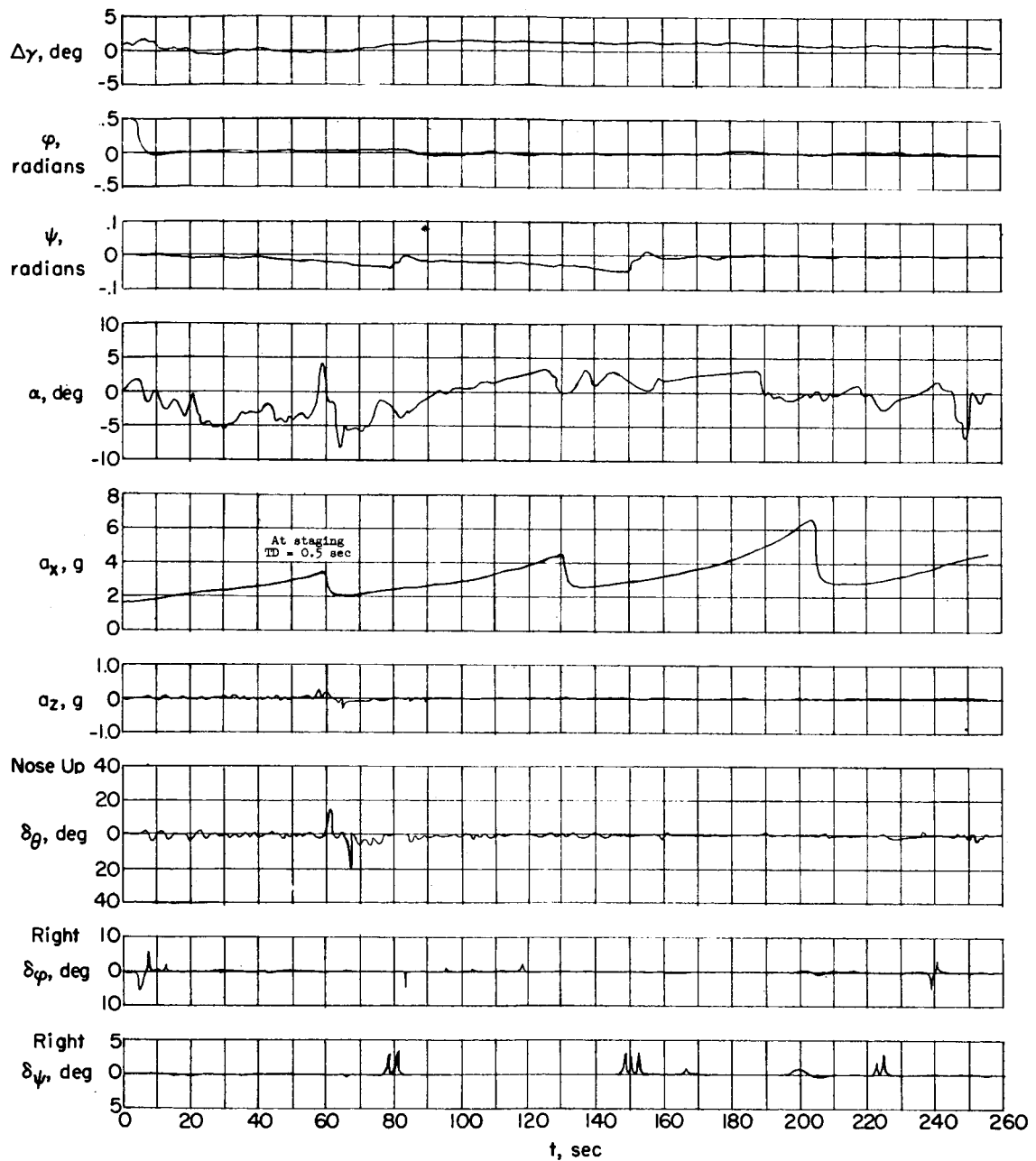
(d) $a_{x_{max}} = 12.4g$.

Figure 7.- Continued.



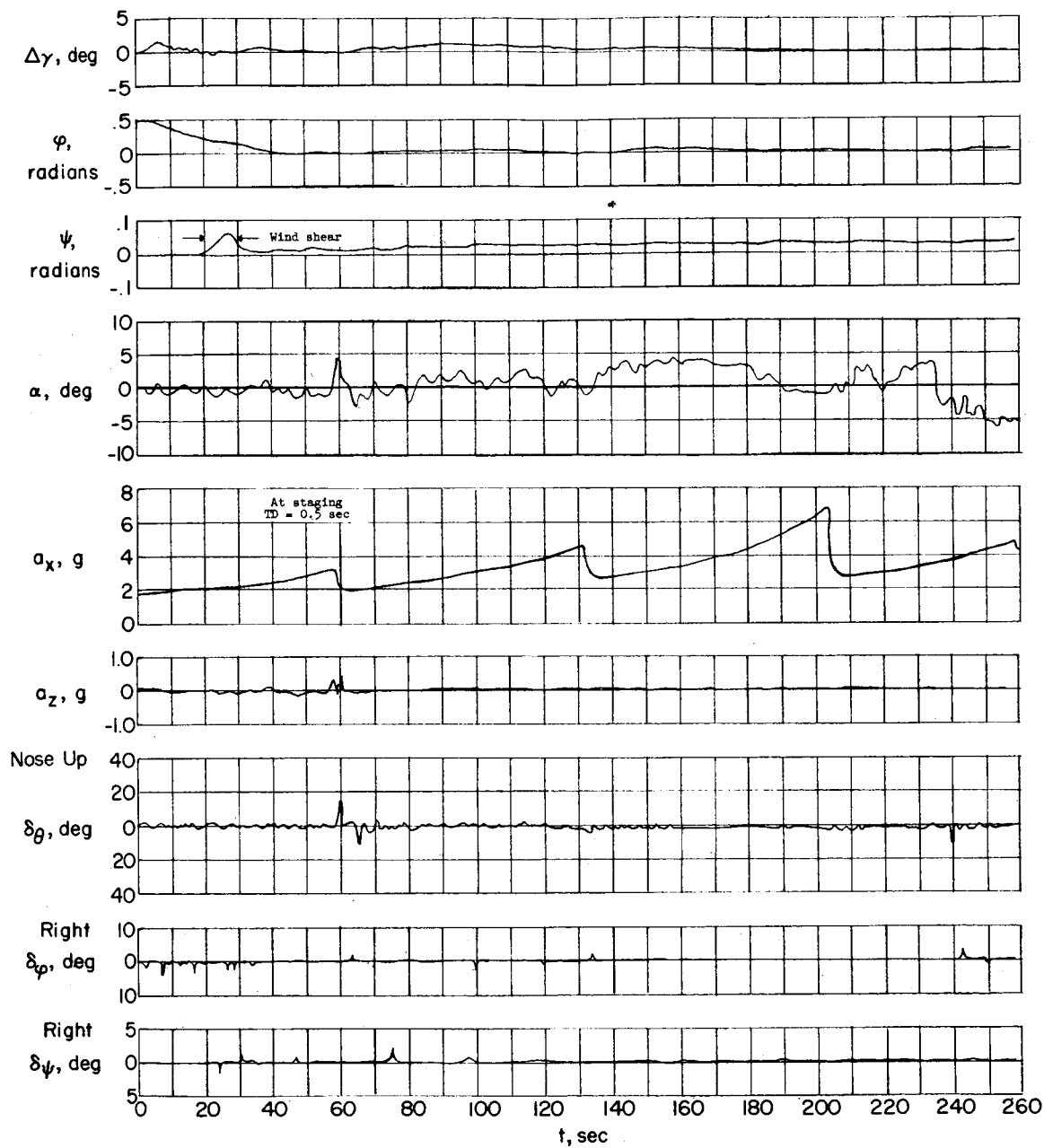
(e) $a_{x_{\max}} = 15g$.

Figure 7.- Concluded.



(a) Static.

Figure 8.- Time histories of static and dynamic four-stage runs.



(b) Dynamic.

Figure 8.- Concluded.

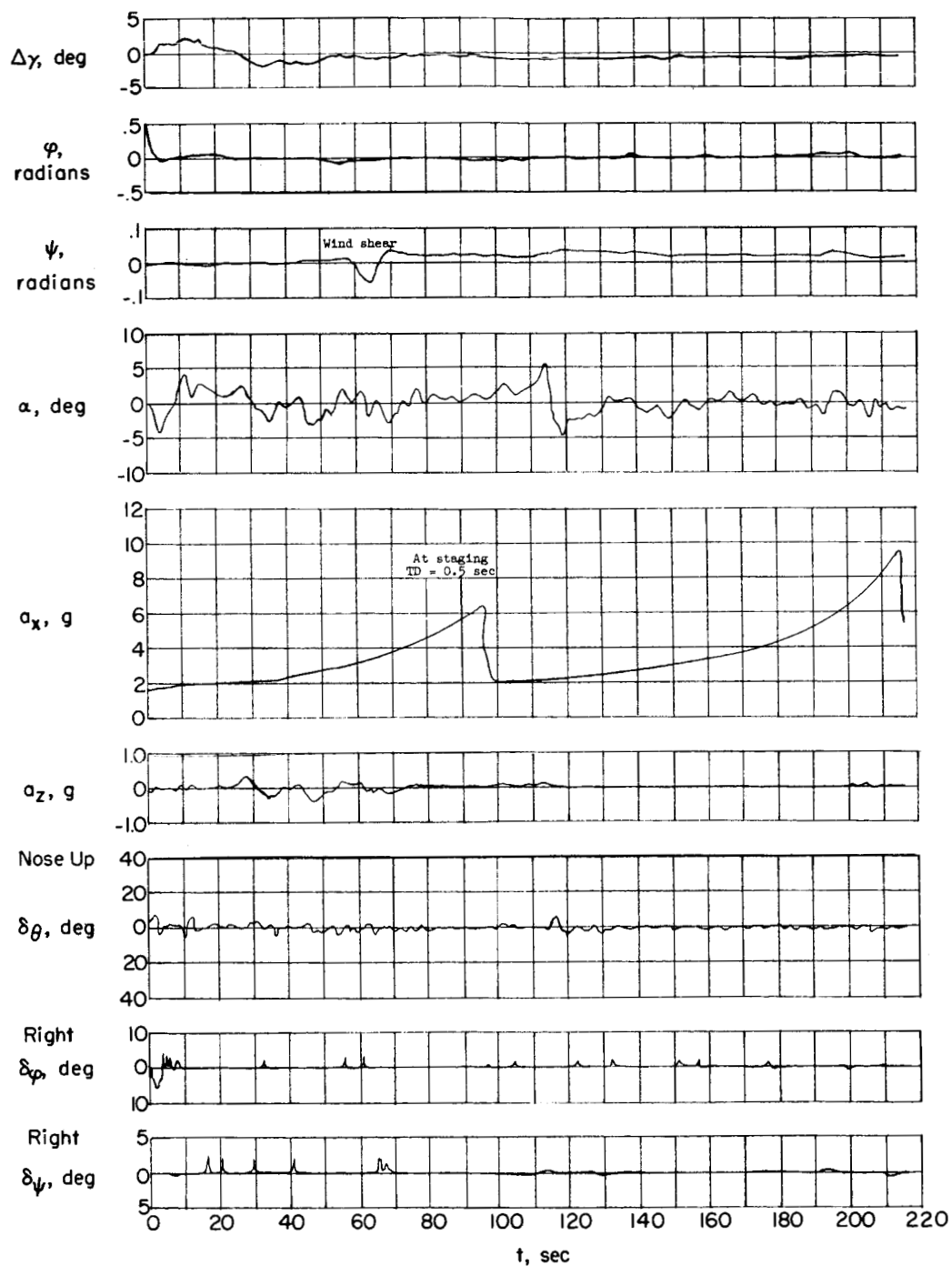


Figure 9.- Time history of dynamic two-stage run.

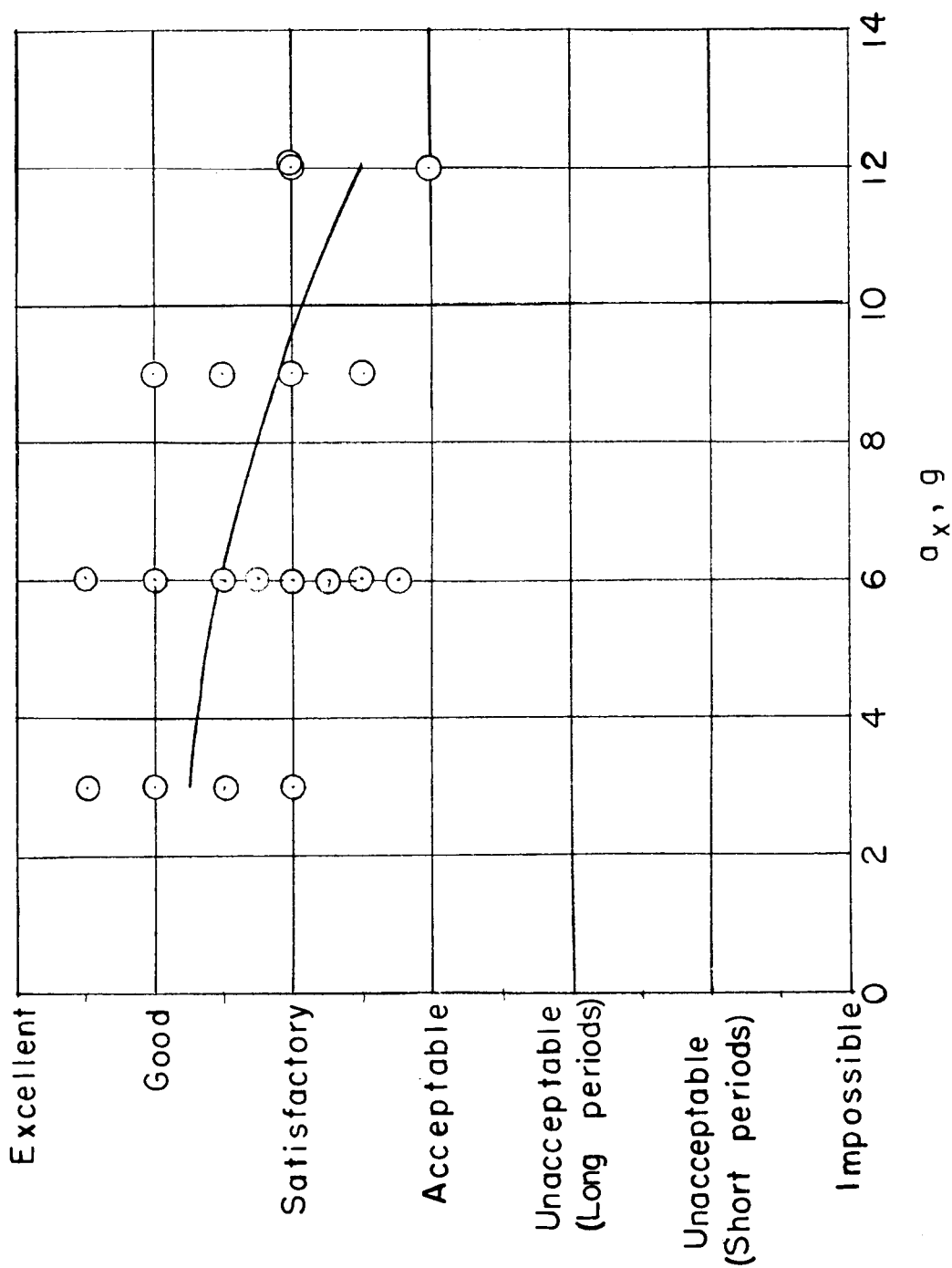
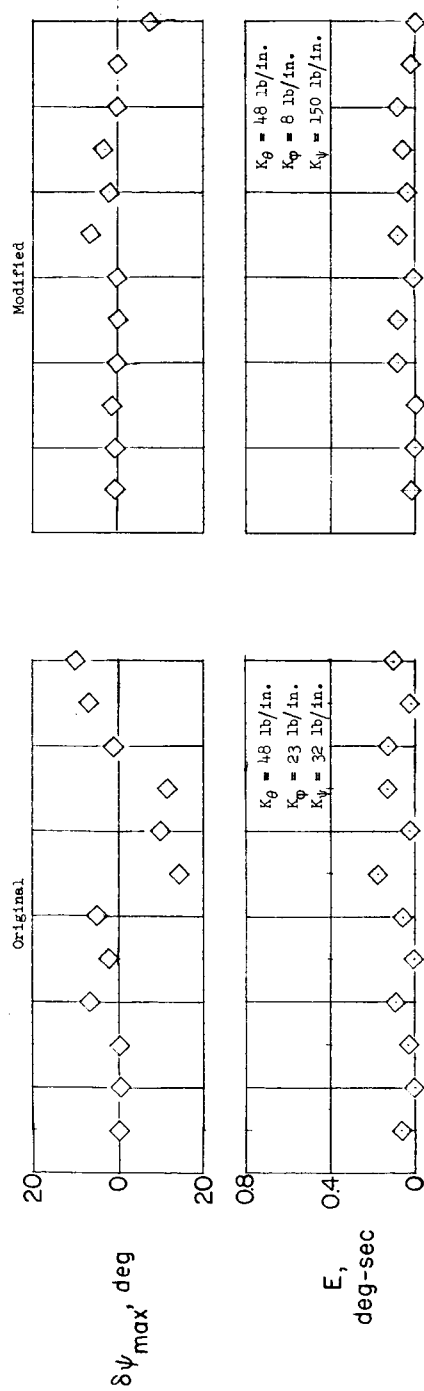
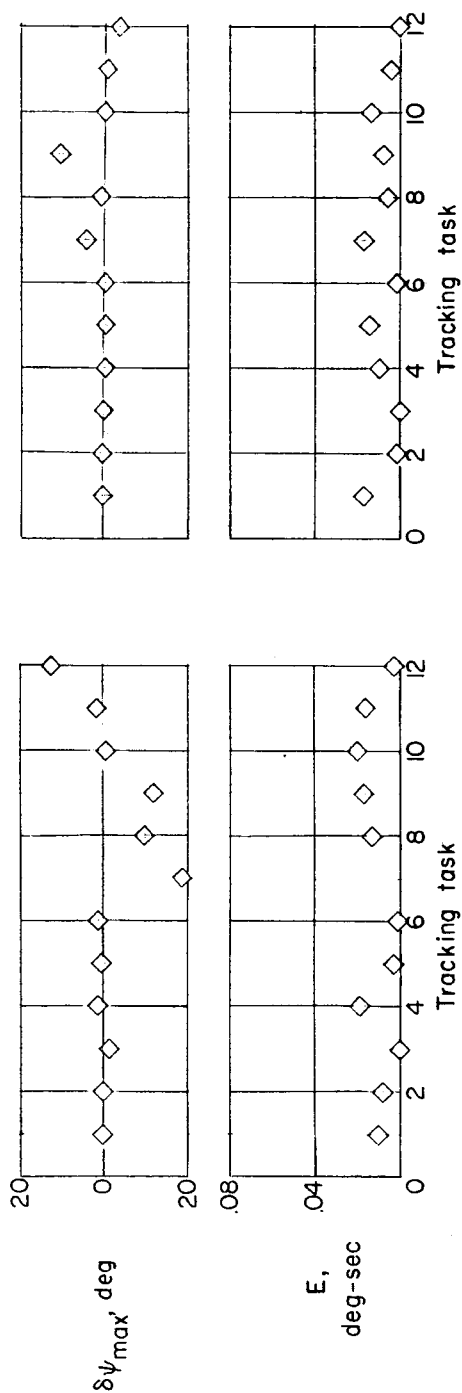


Figure 10.- Summary of the pilots' rating of the controller operation during dynamic centrifuge runs in which peak accelerations reached 3g, 6g, 9g, and 12g.

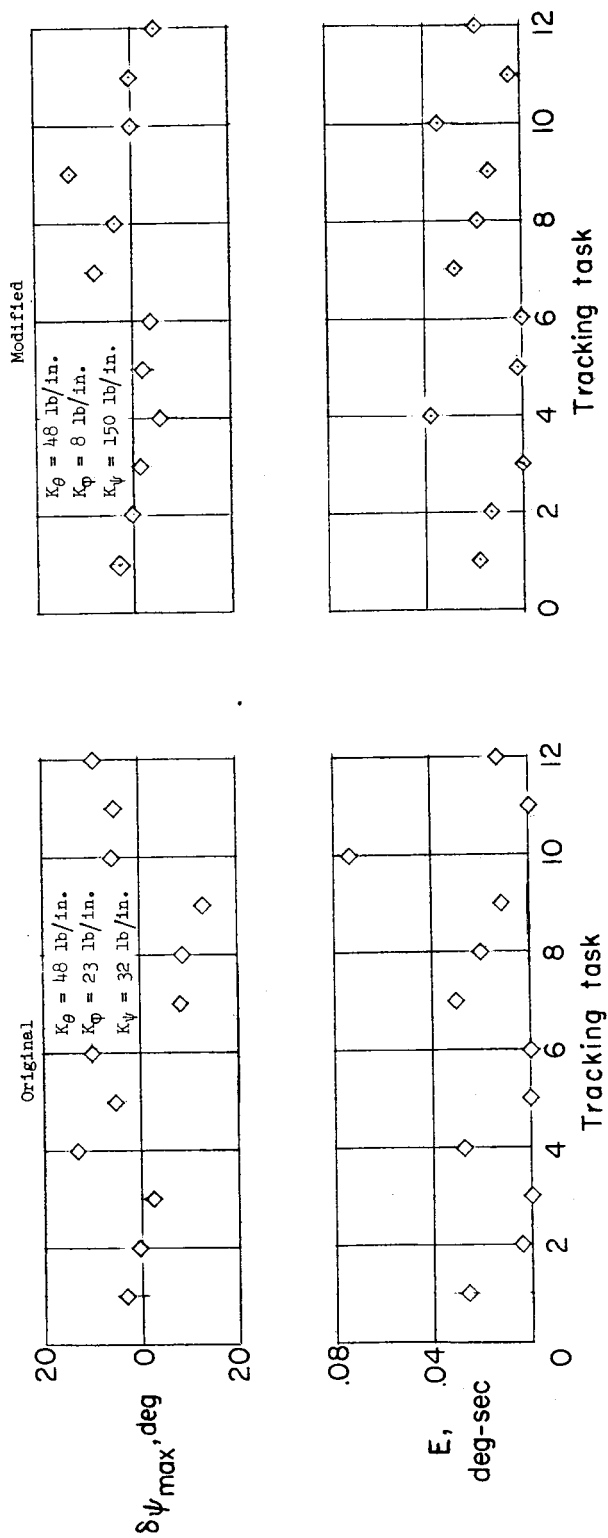


(a) Slow rate.



(b) Medium rate.

Figure 11.- Variation of the maximum inadvertent yaw input and integrated tracking error with control task obtained during the investigation at several rates of control input.



(c) Fast rate.

Figure 11.- Concluded.